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Dennis

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[54] **GPS AND SATELITE NAVIGATION SYSTEM**

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[51] **Int. Cl.**[5] **H04B 7/185**

[52] **U.S. Cl.** **364/449;** 342/357; 342/356; 342/352

[58] **Field of Search** .... 342/352, 356, 357, 451, 342/457; 364/443, 449, 459; 73/178 R

[56] **References Cited**

U.S. PATENT DOCUMENTS

4,445,118	4/1984	Taylor et al.	342/356
4,613,864	9/1986	Hofgen	342/357
4,652,884	3/1987	Starker	342/357
4,751,512	6/1988	Longaker	342/357
4,812,991	3/1989	Hatch	364/458
4,876,550	10/1989	Kelly	342/451
4,879,713	11/1989	Ichiyoshi	370/75
4,894,662	1/1990	Counselman	342/357
4,918,609	4/1990	Yamawaki	364/449
5,017,926	5/1991	Ames et al.	342/357
5,036,330	7/1991	Imae et al.	342/357
5,041,833	8/1991	Weinberg	342/357

FOREIGN PATENT DOCUMENTS

2180426 9/1989 United Kingdom .

OTHER PUBLICATIONS

Paul Massatt and Karl Rudnick, "Geometric Formulas for Dilution of Precision Calculations", *Journal of The Institute of Navigation*, vol. 37, No. 4, pp. 379–391, published in Los Angeles, California, Dec. 1989.

A. R. Dennis, "Special Methods for Using GPS in the Offshore Industry", 12 pages, paper presented at ION GPS-89, Colorado Springs, Colorado, Sep. 27–29, 1989.

Offshore Navigation, Inc., Report on IDGPS Demonstration, 17 pages, published in Houston, Texas, Oct. 1990.

A. R. Dennis, "STARFIX—A New High-Precision Satellite Positioning System", 9 pages, presented at International Symposium on Marine Positioning: INSMAP 86 in Reston, Virginia on Oct. 14–17, 1986.

A. R. Dennis, "New Satellite Positioning System in Operation for Civilian Marine Use", 3 pages, published in *Sea Technology* in Houston, Texas in Sep. 1986.

Rudy Lambert, "Integrating Differential GPS for Higher 3-D Seismic Survey Accuracy", pp. 35–36, 38, Mar. 1992 issue of *Sea Technology.*

Kim Cassis, "STARS—The Second Part of Houston", pp. 24–26, 31–32 in Feb. 1992 issue of DBA.

Interavia, *Space Directory* 1990–1991, pp. 179–181, 395, 405–407, 410–412, published in 1990.

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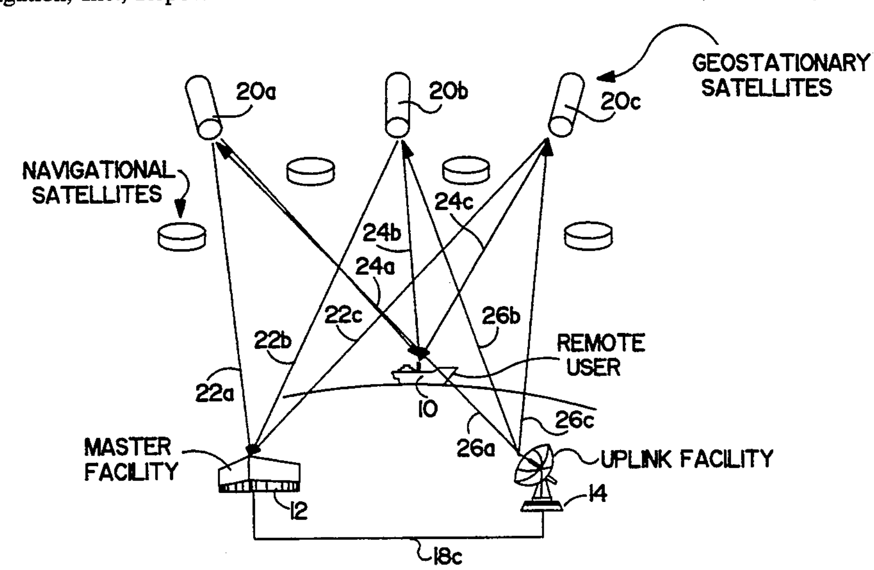
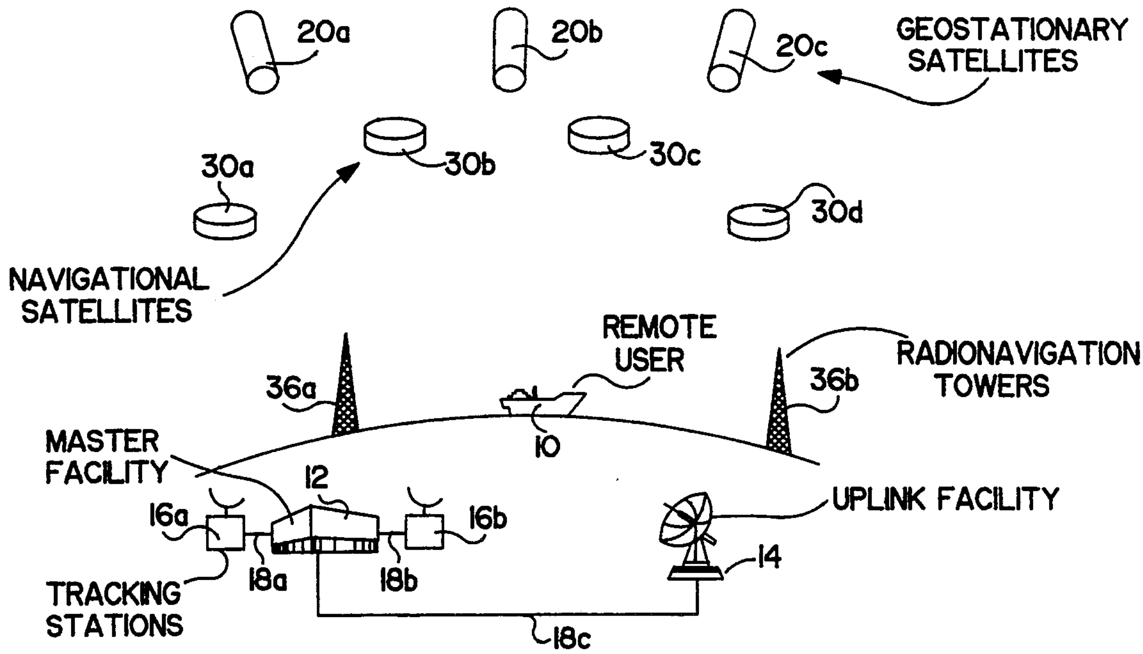
[57] **ABSTRACT**

A satellite-based navigation system providing improved accuracy and reliability over wide geographical areas, including remote regions, is disclosed. Ranging-type signals transmitted through two or more commercial geostationary telecommunication satellites are received at known reference locations where navigation and correction information is generated and transmitted back to remote users. At the same time, the reference stations receive signals from the Global Positioning System (GPS), generate corrections for the GPS measurements, then transmit these corrections to the remote user. The remote user receives all of this information plus direct measurements from both the GPS and the geostationary satellites and, using conditional error processing techniques, provides a position solution whose accuracy and reliability exceeds that of GPS alone.

5 Claims, 4 Drawing Sheets

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20c
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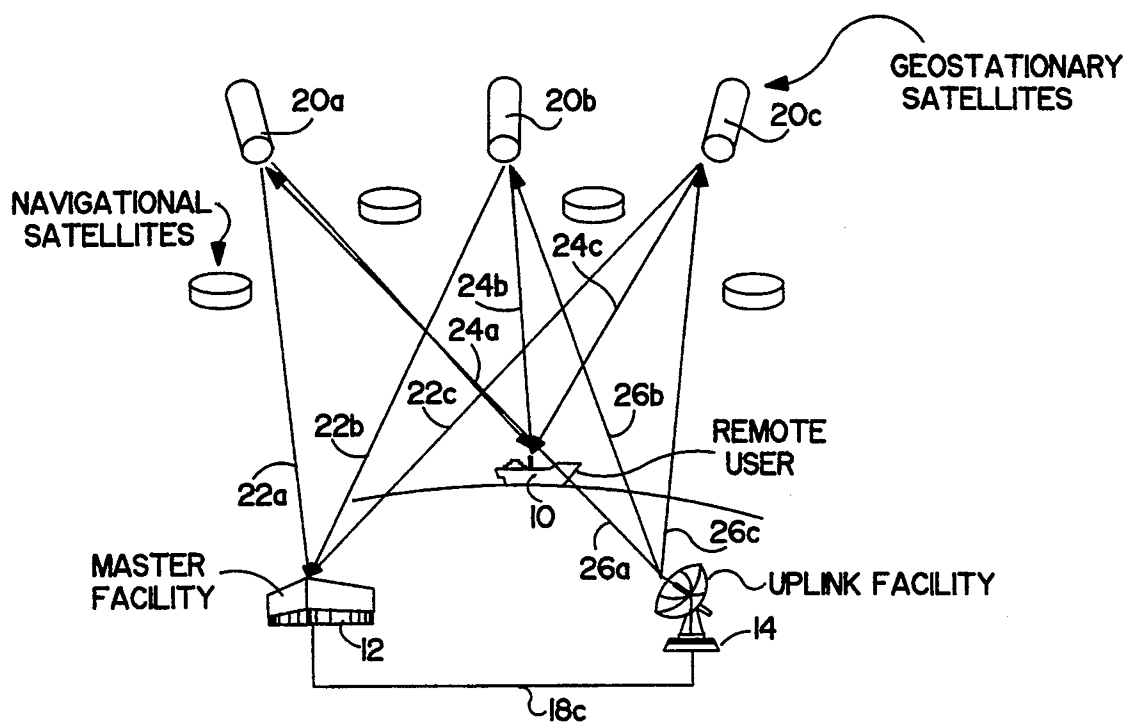
30b
30c
30d
NAVIGATIONAL SATELLITES
REMOTE USER
RADIONAVIGATION TOWERS
36a
36b
10
MASTER FACILITY
12
16a
16b
UPLINK FACILITY
14
18a
18b
TRACKING STATIONS
18c

FIG. 1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NAVIGATIONAL SATELLITES
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22c
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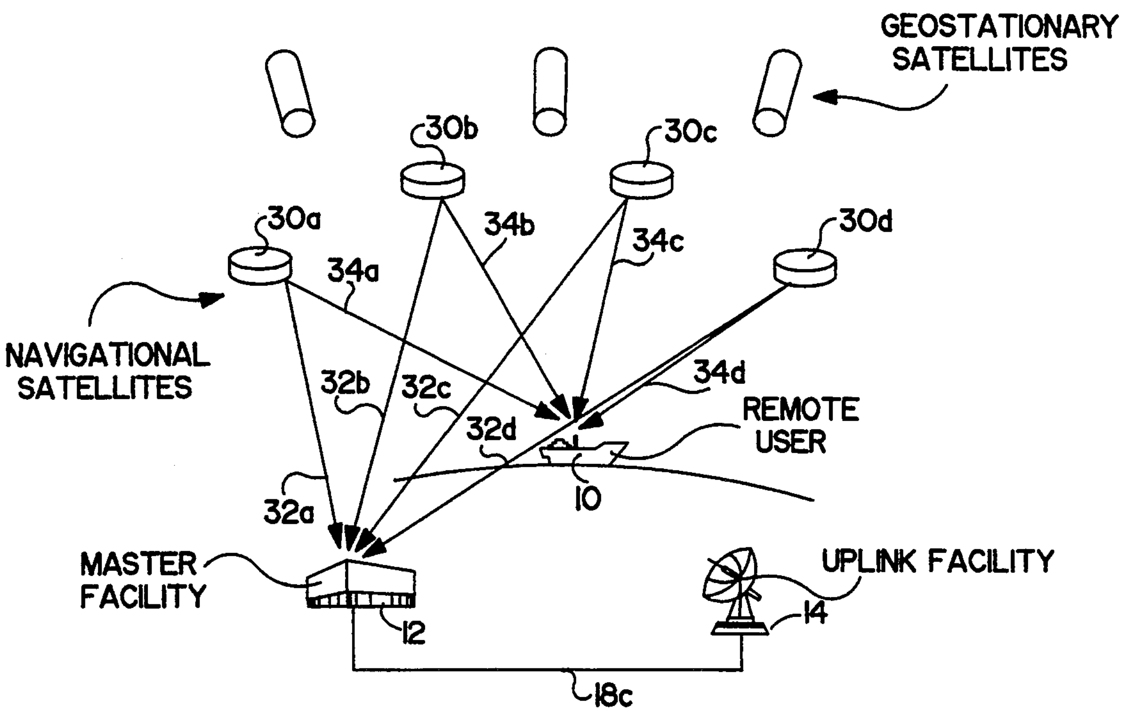
26c
26a
MASTER FACILITY
UPLINK FACILITY
14
12
18c

FIG. 2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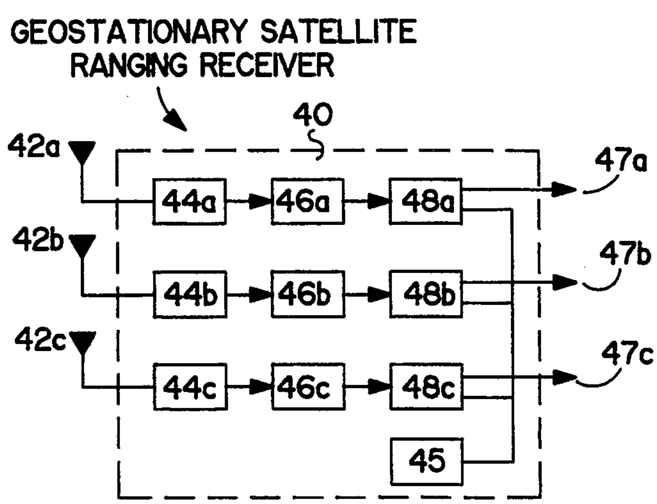
UPLINK FACILITY
12
14
18c

FIG. 3


GEOSTATIONARY SATELLITE RANGING RECEIVER
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42c
44c
46c
48c
47c
45

FIG. 4

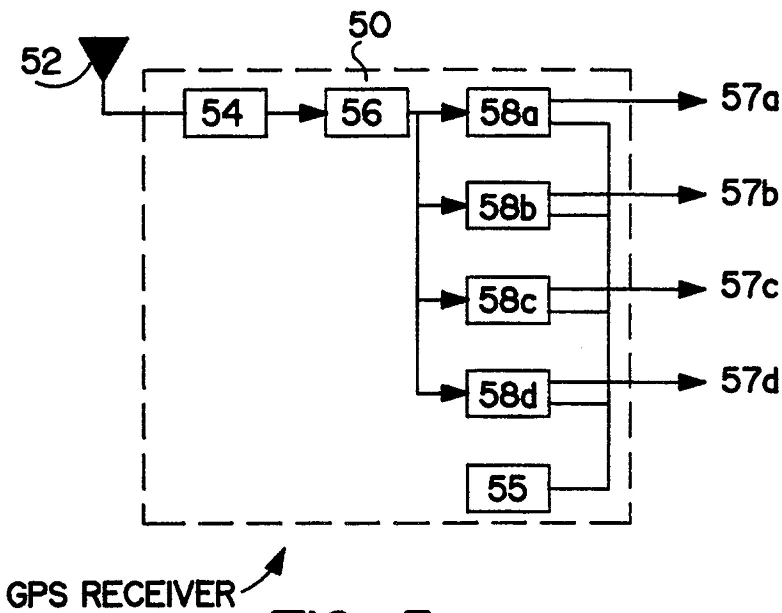

FIG. 5

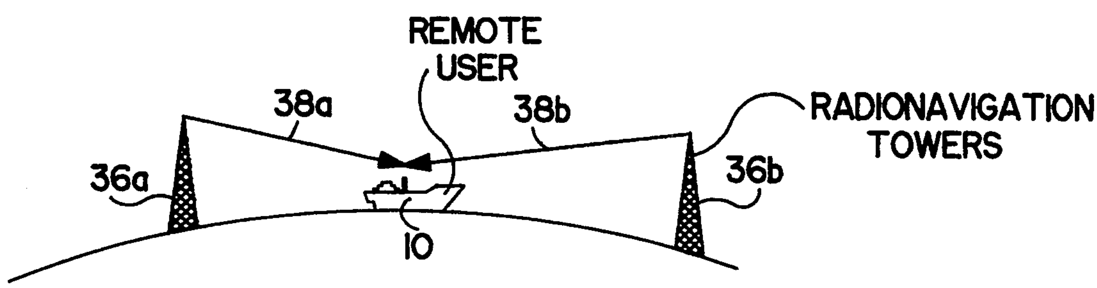

FIG. 6

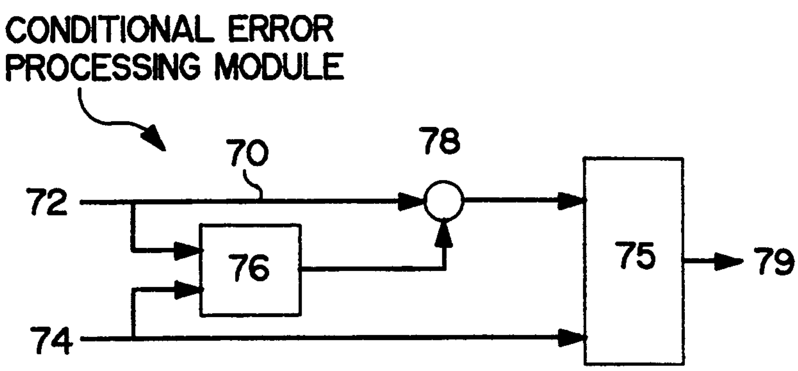

FIG. 7

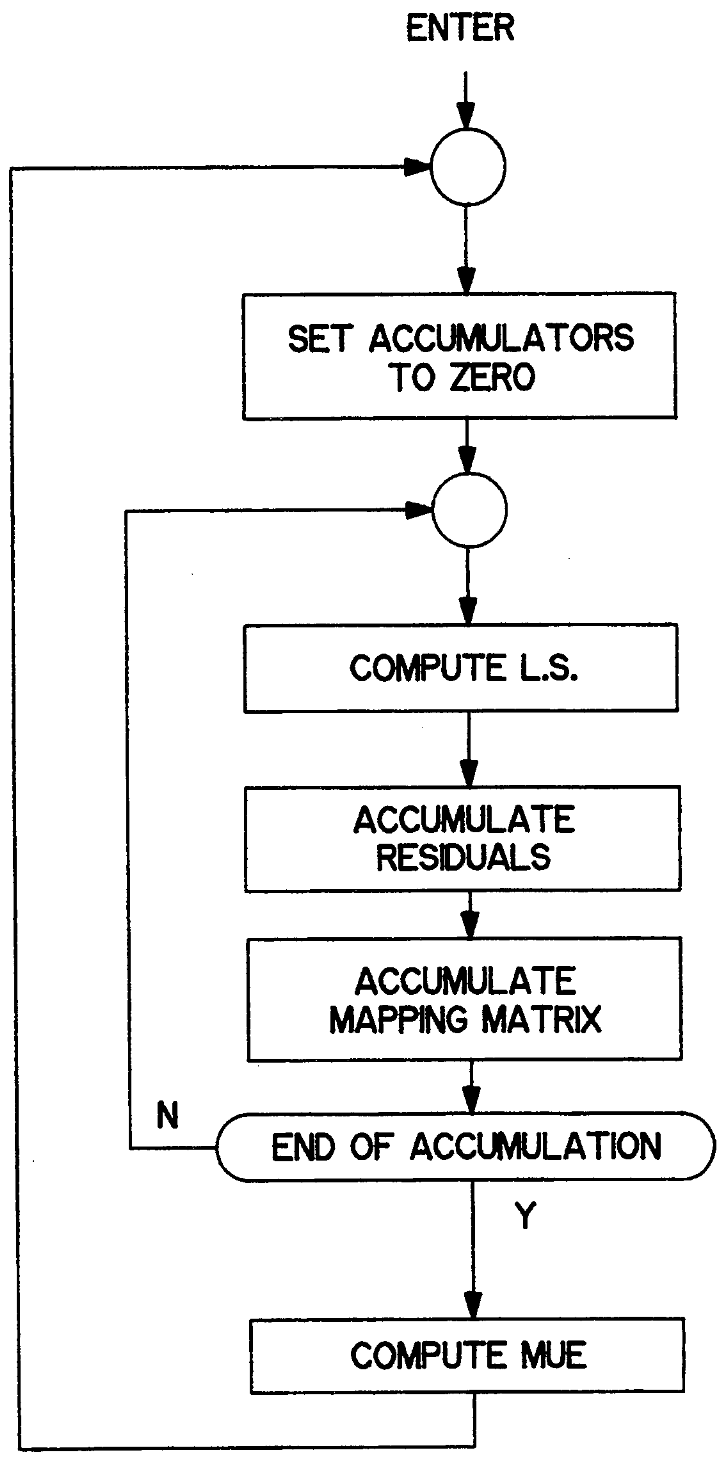
ENTER
SET ACCUMULATORS TO ZERO
COMPUTE L.S.
ACCUMULATE RESIDUALS
ACCUMULATE MAPPING MATRIX
N
END OF ACCUMULATION
Y
COMPUTE MUE

FIG. 8

GPS AND SATELITE NAVIGATION SYSTEM

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention pertains to navigation and positioning systems. More particularly, this invention pertains to a positioning system incorporating navigational satellites and fixed relays in conjunction with a new calibration and processing system to minimize error and obtain more accurate positional coordinates than is possible under current systems.

2. Description of the Prior Art

Navigation by satellite began with the introduction of the U.S. Navy's TRANSIT system in the mid 1960's which is still in use. This system consists of seven polar-orbiting satellites at low-earth altitudes and can provide 20–50 m accuracy. The spread of the satellite orbits allows only one satellite to pass over a given geographic location at a time. Each satellite transmits a beacon-type signal that is received and converted into positional coordinates by analyzing the Doppler effect exhibited by the received signal plus additional navigational information (i.e., the actual satellite positions) transmitted to the TRANSIT user from another source.

A TRANSIT user typically computes a position fix only after each overhead pass is complete, which nominally occurs once every one and one-half hours. The TRANSIT system consequently cannot provide continuous navigational information and only allows the user to update another system, such as dead-reckoning, that provides continuous information. Technical constraints also make the system unusable for vehicles moving at high-speeds.

The United States Government began implementing the next-generation Global Positioning System (GPS) in the late 1970's to provide continuous updates and to service high speed vehicles. GPS employs satellites in 11,000 mile inclined circular orbits spaced 200 Km, 55° apart and will provide a user with continuous coverage anywhere on earth once the full constellation of satellites is properly placed in orbit. The orbits and operating parameters of GPS satellites are well known to those of ordinary skill in the art and are readily available to the public through various sources. One such reference is the *Interavia Space Directory* (1990–1991) available from Jane's Information Group and another is the *World Satellite Almanac* (2d Ed.) authored by Mark Long and published by Howard N. Sams & Co.

Each GPS satellite transmits an encrypted signal for military use and a degraded, unencrypted signal for civilian use. GPS satellites continuously broadcast signals that may be received by anyone with the proper equipment. These carrier signals are superimposed with the respective satellite's ephemeris that must be determined from the content of the GPS signal by the user's software in addition to the three dimensions of position. GPS operates on the principle of multilateration wherein a user determines the intersection of a plurality of range measurements derived from the GPS signals, the range measurements being made simultaneously to separate GPS satellites. The user then ascertains from this intersection his instantaneous latitude, longitude, and altitude.

The range measurements inherently contain an error called an offset bias common to all the measurements created by the unsynchronized operation of the satellite and user clocks. This error will yield an erroneous range measurement, making it appear that the user is either closer to or farther from each of the satellites than is actually the case. These measurements are therefore more accurately termed pseudoranges. Four or more measurements are therefore to ascertain the unknown latitude, longitude, altitude, and offset bias required since the measurements are not truly ranges but are instead pseudoranges obtained from the signals of the respective GPS satellites.

GPS has some serious shortcomings, especially for continuous coverage with five meter accuracy, resulting from several factors. Physical factors include uncertainty in (1) atmospheric propagation delays, (2) precise GPS satellite locations, (which are required to determine a fix), and (3) the accuracy of the timing information that provides the basis of the pseudoranges. Induced errors include intentional degradation by the United States Department of Defense of the unencrypted signal for civilian users, from approximately 25 m accuracy to 100 m accuracy or worse for national security reasons. The best currently available techniques for overcoming this error can only reduce it to about 15 m.

One way of reducing the effects of the error in GPS produced by these factors utilizes differential corrections for the pseudoranges measured by the user to eliminate common errors, namely offset biases. Differential corrections are determined by placing a GPS receiver at a precisely known, fixed reference site, and then measuring the actual errors by comparing the received pseudoranges with the values expected for the known reference site. The differences between the received and expected values are then transmitted to users over a separate communication link to correct their pseudorange measurements before the user's position, i.e., the "fix", is computed.

However, some fix errors are residual and cannot be totally compensated for by differential correction. For example, atmospheric propagation delay errors and satellite

PATENT position errors will vary as the distance from the reference site increases and therefore will not be common to all measurements. A method for reducing the sensitivity of the user fix computation to residual error must also be employed in addition to differential correction.

Sensitivity to residual error depends on the satellite locations with respect to the user's location and the consequent mathematical relationship between basic pseudorange measurement errors and the position computation. This mathematical relationship is called the Position Dilution of Precision (PDOP) and its existence and affect are well known to those of ordinary skill in the art. One treatment of the topic may be found in the publication "Geometric Formulas for Dilution of Precision Calculations", authored by Paul Messett and Karl Rudnick, and published in Vol. 37., No. 4 at page 379 of the *Journal of the Institute of Navigation.* PDOP is a primarily scaler multiplier that allows the user to estimate fix uncertainty for a given measurement uncertainty. For example, if the measurement error is ±10 meters and the PDOP is 3, the user can expect a fix error (i.e., error in calculated position) of ±30 meters in a statistical sense.

GPS satellite locations are constantly changing as the satellites move across the sky and so the PDOP also constantly changes regardless of whether the user is stationary. Minimum PDOP occurs when all satellites are uniformly distributed across the sky seen by the user but this does not occur all the time. Users sometimes experience very large PDOP, especially when the satellites become "grouped together", and fix errors correspondingly fluctuate.

There have been previous attempts to reduce PDOP or otherwise improve the accuracy of GPS-based positioning for remote moving users. U.S. Pat. No. 4,812,991 discloses a technique in which assorted GPS measurements are combined in a prescribed manner to reduce the effect of measurement errors. This technique does not reduce the effective PDOP governing the relationship between measurement errors and fix errors or extend the useful coverage of GPS as does the present invention.

U.S. Pat. No. 4,876,550 describes another data processing method which, although not specifically directed at GPS-based positioning, could be used to reduce the effect of nearly-singular geometry (large PDOP) on position fix computations. This method also does not reduce the typical effective PDOP but instead is applicable when the PDOP is so high that it is essentially infinitely large. This is not generally applicable to GPS which is designed to provide reasonable PDOP at all times although the PDOP will still be too large for accurate positioning because of measurement errors.

Alternative geostationary satellite-based systems have been proposed in order to minimize dependence on GPS with its attendant problems. These systems exhibit large latitudinal PDOP because all of the satellites necessarily reside in the earth's equatorial plane. The relatively large PDOP can magnify small errors in height calculation or instrument calibration to cause large latitudinal position errors. The achievable accuracy from these systems does not meet all needs but the coverage they provide is ideal since the satellites are always in view.

Some approaches have also attempted to use privately developed shore-based navigation systems. These systems can be very accurate but are affected by atmospheric variations, even to the extent that some longer range systems are unstable at night. Also, the construction and maintenance of shore based stations may be logistically or politically unfeasible in many parts of the world.

For some critical applications such as public safety and energy exploration, large increases in PDOP are intolerable. Occurrence of PDOP variations caused by changing satellite position can be reduced, as can PDOP itself, by integrating GPS measurements with those made to one or more commercial geostationary communication satellites. Since these geostationary satellites are earth-stationary, their effective PDOPs are virtually constant. Thus, when measurements from geostationary satellites are combined with those from GPS, the overall PDOP is "smoothed out" and large latitudinal errors inherent in geostationary satellite systems can be eliminated.

A system is described in United Kingdom Patent No. 2,180,426 that combines GPS with a geostationary communication satellite to provide a combined navigation/communication capability. A GPS-like signal is transmitted from the communication satellite, presumably for navigational purposes. However, the requirement to synchronize the clock of this signal to the GPS clock is virtually impossible to realize because of circuit delays and other transponder limitations found in commercial communication satellites. No description of how the combined positioning would be accomplished is provided even if satisfactory timing could be realized (e.g., how the location of the communication satellite derived). The concept is unworkable as described.

An intrinsic calibration problem arises when combining GPS and geostationary-based measurement. Unlike GPS where the carrier frequencies are all the same, geostationary satellite signals pass through different receiver and transponder circuits which necessarily create different time delays thereby introducing instrumental biases. These instrumental biases are difficult to determine for a moving user because each received signal has a different frequency requiring separate receiving and processing channels so that switching channels is impractical.

This calibration problem renders the usual software solution for determining common measurement delays applied to GPS signals ineffective. Although instrumental biases can be minimized through instrumentation calibration, they may change at any time afterwards due to environmental factors and dynamic effects for moving users. A new method must be found to eliminate instrumental biases in geostationary satellite measurements in realtime.

It is therefore a feature of this invention that it reduces PDOP variations in obtaining positional coordinates.

It is a further feature of this invention that it minimizes the affect of PDOP in obtaining measurements.

It is a still further feature of this invention that it both compensates for unequal instrument delays and determines and eliminates residual error in the measured data in real time.

It is another feature of this invention that it detects and eliminates instrument biases and residual errors using the entire measurement data set.

It is still another feature of this invention that it employs a unique statistically oriented method for detecting and eliminating error in the data set.

It is a further feature of this invention that it integrates navigational satellite data with geostationary satellite data to obtain more accurate positional coordinates.

It is yet another feature of this invention that it provides positional coordinates that are more accurate than can be obtained from conventional techniques.

It is a further feature of this invention that it relies primarily on existing satellite and telecommunication hardware to reduce the cost of implementing the system.

SUMMARY OF THE INVENTION

This invention improves the accuracy and reliability of satellite-based navigation by combining in its preferred embodiment measurements derived from GPS and commercial geostationary satellite systems in the position computation. Differential corrections are determined for both GPS and geostationary satellite signals and transmitted to the user. The use of geostationary satellites provides enhanced coverage and accuracy over the use of GPS alone since the signals emanate from stationary points rather than from moving satellites that rise and fall. The GPS satellite measurements increase positioning accuracy since they afford better spatial geometry. The measurements are then combined by the user employing a unique method that improves error detection and removal as compared with previously used techniques.

BRIEF DESCRIPTION OF THE DRAWINGS

A more particular description of the invention briefly summarized above may be had by reference to the exemplary preferred embodiments illustrated in the drawings of this specification so that the manner in which the above cited features, as well as others which will become apparent, are obtained and can be understood in detail. The drawings nevertheless illustrate only typical, preferred embodiments of the invention and are not to be considered limiting of its scope as the invention may admit to other equally effective embodiments.

In the Drawings:

FIG. **1** illustrates the major components of the preferred embodiments;

FIG. **2** depicts the use of geostationary communication satellites to comprise a subsystem of fixed relays in accord with the first preferred embodiment of the invention;

FIG. **3** depicts the use of navigational satellites to comprise a subsystem in accord with both preferred embodiments of the invention;

FIG. **4** is a block diagram of a geostationary satellite signal receiver for use with the invention;

FIG. **5** is a block diagram of a GPS signal receiver for use with the invention;

FIG. **6** shows an alternative preferred embodiment employing radionavigation towers rather than geostationary communications satellites;

FIG. **7** is a block diagram of the conditional error processor of the preferred embodiment of the invention; and

FIG. **8** is a flow diagram of the steps performed by the conditional error processor of FIG. **7**.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Most of the major components of the present invention are illustrated in FIG. **1**. Remote user **10** is located at some uncertain position and may be relatively rapidly moving. Remote user **10** has at least one geostationary satellite signal receiver **40** as is diagrammed in FIG. **4** and at least one GPS signal receiver **50** as is diagrammed in FIG. **5**. Remote user **10** receives signals from each of geostationary satellites **20***a–c* via receiver **40** and from each of navigational satellites **30***a–d* via receiver **50**.

Geostationary telecommunication satellites **20***a–c* may be any of several types well known to those of ordinary skill in the art whose services are commercially available for lease. Geostationary satellites are in a fixed relationship to a particular location or the earth and consequently operate as "fixed relays" receiving signals and relaying them to a predetermined location. The commercial services of the Galaxy, Westar, Satcom, and Spacenet satellites are all suitable for implementing the present invention.

Telecommunication satellites **20***a–c* receive and transmit spread spectrum signals modulated with a pseudorandom (PRN) code sequence at prescribed chipping and code repetition rates to prevent interference with other signals within the carrier band. These spread spectrum signals must be authorized common carrier signals duly licensed for transmission and receipt by the appropriate governmental entities. In the United States, this is primarily the Federal Communications Commission (FCC).

Modulation of spread spectrum signals associated with satellites **20***a–c* includes low frequency biphase modulation of the carrier signal containing information necessary for performing navigational computations aboard remote user **10**. The information bandwidth of the signals received and transmitted by geostationary satellites **20***a–c* in the preferred embodiment of the invention is on the order of 100 Hz. The pseudorandom code sequence chipping rates are typically in the range of 2.5 mHz and code repetition rates are typically in the range of 150 Hz. Satellites **20***a–c* receive signals from uplink facility **14** and transmit signals to both remote user **10** and master facility **12** as shown in FIG. **2**.

Navigational satellites **30***a–d* in the preferred embodiment are GPS satellites whose operating parameters were discussed in part above. Additionally, the carrier signals from each GPS satellite are modulated with a unique pseudo-random (PRN) code sequence, one at chipping rates of 1.023 mHz and the other at 10.23 mHz. Each carrier signal also contains its respective satellite's ephemeris containing its precise location at any given time.

Master facility **12**, uplink facility **14**, and tracking stations **16***a–b* comprise a means for receiving and transmitting signals to and from satellites **30***a–d* and **20***a–c* and to remote user **10**. Tracking stations **16***a–b* and uplink facility **14** are linked to master facility **12** via communication links **18***a–c*, respectively. The means for receiving and transmitting necessarily has a GPS receiver **50** and a geostationary satellite signal receiver **40**, generally located at master control facility **12**, for receiving signals.

Tracking station **16***a–b* are representative of a remote tracking network that may be comprised of as many such tracking stations as is required, but all embodiments require at least four tracking stations. Neither the tracking network nor uplink facility **14** need necessarily be in close physical proximity with master control facility **12**. It is generally desirable that the tracking network have a high number of tracking stations widely distributed throughout the coverage area.

Master facility **12** coordinates receipt and transmission of the various signals received by and transmitted from tracking stations **16***a–b* and uplink facility **14** as well as modulation and error correction of data in selected signals as described below. Uplink facility **14** transmits timing-based, modulated, conventional common carrier frequency signals such as C-band or Ku-band signals. This modulation in the preferred embodiment of the invention is a spread spectrum pseudorandom code (PRC) originating in a stable oscillator such as an atomic clock.

One important aspect of the invention is that little or no capital is required to implement the most expensive equipment necessary for the practice of the invention. The GPS satellite system is largely in place and is a project of the United States federal government. The geostationary telecommunications satellites are also in place and their services are readily obtainable along with equipment for receipt, processing and transmission of signals. Access to and use of equipment comprising geostationary satellites **20***a–d*, master control facility **12**, tracking stations **16***a–b*, communications links **18***a–c*, and uplink facility **14** can be obtained by contacting a single sales representative at a commercial teleport as may commonly be found in many major American metropolitan areas.

Another important feature is that the receipt, processing and transmission of all signals employs standard spread spectrum signal technology and so can be used with "off-the-shelf" technology. The sole exception is the conditional error processing described below that is performed by the user. Thus, most of the technology for implementing the invention is readily accessible to the public in sources such as *World Satellite Almanac* published by Howard W. Sams & Company and *Spread Spectrum Systems* authored by Robert C. Dixon and published by John Wiley & Sons in addition to commercial teleports and the Interavia *Space Flight Directory* mentioned above.

Receivers **40** and **50** aboard remote user **10** and located at master control facility **12** track the PRC signals generated at uplink facility **14** and, through correlation techniques, generate a signal that accurately tracks the timing provided by uplink facility **14**. The output generated by receivers **40** and **50** contains the measured pseudoranges that are proportional to the range from user **10** to the fixed relays and navigational satellites, respectively. These signals also include errors created by offsets between the clocks of uplink facility **14** and remote user **10** as well as propagation errors incurred in the earth's atmosphere and satellite transponders.

The geostationary satellite ranging receiver, generally denoted **40**, is illustrated in FIG. **4** in block diagram form. Antennas **42***a–c* are, in the preferred embodiment, small directional antennas that must be pointed at satellites **20***a–c* to achieve the highest gain and background signal rejection. Antennas **42***a–c* receive signals broadcast by each of satellites **20***a–c*, respectively, which signals are then amplified and converted by RF sections **44***a–c*, respectively. The PRN code sequence is tracked in code tracking loops **46***a–c*, respectively, and the code phase is measured in code phase loops **48***a–c*, respectively, with respect to local oscillator **45**.

Outputs **47***a–c* consist of pseudorange signals transmitted by satellites **20***a–c* and received by antennas **42***a–c*, after data receipt and processing. Multiple antennas, channels, and outputs are necessary because each geostationary satellite will typically transmit on different frequencies and will thus necessitate separate circuits for receipt and processing. Receiver **40** will also output data representing the referenced pseudoranges received from master control facility **12** and the position of satellites **20***a–c*.

The GPS receiver of the preferred embodiment of the invention, generally denoted **50**, is illustrated in block diagram form in FIG. **5**. A single omni-directional antenna **52***a*, radio frequency amplifier **54***a*, and code tracking loop **56***a* are employed because satellites **30***a–c* transmit on the same frequencies. Code tracking loop **56***a* then discriminates between signals originating from each of satellites **30***a–d* by virtue of their unique PRN code sequences and separates them out for transmission to their respective code phase loops **58***a–d*. Code phase loops **58***a–d* also compare their respective signals to local oscillator **55** for operational purposes to provide the pseudorange measurements output at **57***a–d*.

There are commercial products available that may be used to implement receivers **40** and **50** of the invention. Geostationary satellite receiver **40** can be one of many c-band communication receivers capable of handling spread-spectrum downlink signals. The preferred embodiment employs the VSAT receiver manufactured by Contel for their VSAT point-to-multipoint low data rate communications services. GPS receiver **50** similarly may be one of many commercial products, and GPS receivers manufactured by Trimble, Magnavox, and Motorola are preferable.

Turning to the operation of the geostationary communication satellite subsystem shown in FIG. **2**, uplink facility **14** transmits spread spectrum signals via signal paths **26***a–c* to satellites **20***a–c*, respectively, in a common carrier, uplink frequency band. Satellites **20***a–c* then retransmit them as relay signals via signal paths **22***a–c*, respectively, to master control facility **12** and as relay signals via signal paths **24***a–c*, respectively, to remote user **10** at different downlink frequencies. The relay signals are received at master control facility **12** and remote user **10** via signal paths **22***a–c* and **24***a–c* simultaneously. These relay signals may be of differing carrier frequencies within the downlink carrier frequency band that are modulated with the same pseudorandom code sequences and at the same chipping and code repetition rate.

Tracking stations **16** and **18** are also employed in conjunction with the geostationary satellite subsystem of FIG. **2**. Signals are transmitted from uplink facility **14** to satellites **20***a–c* whereupon they are relayed to tracking stations **16***a–b*. Tracking stations **16***a–b* each have at least one receiver **40**. Information generated at tracking stations **16***a–b* is transmitted to master control facility **12** via communication links **18***a–b*, respectively.

The operation of the navigational satellite subsystem is illustrated in FIG. **3**. Each of satellites **30***a–d* transmits a signal that is received simultaneously at remote user **10** and master control facility **12** via signal paths **32***a–d* and **34***a–d*. As previously mentioned, master control facility **12** has a GPS receiver such as receiver **50** in FIG. **5** that receives the signal broadcast by each of satellites **30***a–d* to provide pseudorange measurements for each satellite relative to a precisely known antenna location at master control facility **12**. Differential corrections to the pseudoranges are then computed to obtain new values for the pseudoranges so that they are accurate at the known location.

These differential corrections are periodically transmitted by master control facility **12** to uplink facility **14** via communication link **18***a* where they are transmitted to user **10** via telecommunication satellites **20***a–c*. Remote user **10** then receives those corrections via receiver **40** in FIG. **4** and applies the corrections to his measured pseudoranges obtained from the signal broadcast by satellite **30***a–d* before processing.

Calibration to eliminate instrumental biases introduced by separate channels in receiver **50** tends to eliminate such biases because each of satellites **30***a–d* effectively transmits its signal at the same time and at the same frequency. Remote user **10** can compare each of the signals to insure that they exhibit the same delay with respect to the GPS receiver clock **55** and adjust them accordingly utilizing differential correction techniques. Thus the output of any GPS receiver at user **10** master control facility **12** will be largely free of instrumental biases and is self-calibrating in this respect.

Master control facility **12** receives signals relayed from each of geostationary satellites **20***a–c* and transmitted from navigational satellites **30***a–d* as previously described. Master control facility **12** has at least one receiver akin to receiver **40** in FIG. **4** and one akin to receiver **50** in FIG. **5** for this purpose. Each receiver generates a pseudorange measurement by measuring the epoch of the received code sequence with respect to an independent oscillator or clock (not shown) at master facility **12**. The measurement is a code phase measurement proportional to the range from master facility **12** to the respective satellite but contains an arbitrary offset introduced by the clock of master control facility **12**.

Five sets of pseudoranges are generated in the preferred embodiment of this invention:

(1) geostationary satellites **20***a–c* relative to user **10**;

(2) geostationary satellites **20***a–c* relative to master control facility **12**;

(3) geostationary satellites **20***a–c* relative to tracking stations **16***a–b;*

(4) navigational satellites **30***a–d* relative to user **10**; and

(5) navigational satellites **30***a–d* relative to master control facility **12**.

Once generated, those pseudoranges not generated at user **10** but needed to generate correction data are transmitted to user **10** for use in computing a fix.

The pseudorange measurements with respect to geostationary satellites **20***a–c* relative to master control facility **12** are made simultaneously, thereby obtaining a set of data represented by Equation 1:

$$Z_M = R_M + D_M + D_U + N_M \quad [1]$$

where

Z_M = the vector of the measured pseudoranges at master control facility **12**;

R_M = the vector of ranges from master control facility **12** to the respective geostationary satellites;

D_M = the vector of common clock offsets by the clock of master facility **12**;

D_U = the vector of transponder delays in respective geostationary satellites; and

N_M = vector of the measured random noise at master control facility **12**.

Pseudorange measurements made at master control facility **12** using Eq. 1 are reference pseudorange measurements that are sent to uplink facility **14** via communication link **18***c*. Uplink facility **14** also has a local clock (not shown) from which the PRN codes are derived, as well as a modulator (also not shown). The modulator of uplink facility **14** accepts the data from master control facility **12** and modulates it onto the uplink carrier signal in a manner well known to those of ordinary skill in the art. The clock of uplink facility **14** does not introduce error or delay and consequently has no bearing on the generation of user measurements, but should nevertheless be stable enough to create slowly varying pseudorange measurements of both master control facility **12** and remote user **10**. A carrier signal modulated with the master pseudorange data is then transmitted to remote user **10**.

Simultaneously, pseudorange measurements with signals from the geostationary satellites **20***a–c* are calculated at remote user **10**. These measurements can be represented by Eq. 2:

$$Z_U = R_U + D_U + D_U + N_U \quad [2]$$

where

Z_U = the vector of measured pseudoranges at remote user **10**;

R_U = vector of ranges from user **10** to the respective geostationary satellite;

D_U = vector of the common clock offsets of the clock at remote user **10**;

D_{UG} = vector of transponders delays at the respective geostationary satellites; and

N_U = vector of measurement of random noise at remote user **10**.

Transponder delay D_U is common to Eqs. (1) and (2) and can be eliminated by taking their difference to obtain:

$$Z_D = (R_U - R_M) + (D_U - D_M) + (N_U - N_M) \quad [3]$$

A major source of instrumental bias is thereby eliminated, including all delays and offsets produced at master control facility **12**, uplink facility **14**, and propagation delays incurred in signal transmission along signal paths associated with satellites **20***a–c*. This significantly eliminates the need to transmit timing information and overcomes synchronization problems found in the art.

Eq. (3) shows that the Z_D is a function of four unknowns: the three cartesian coordinates latitude, longitude, and altitude of user 10's position and the common clock differences offset $(D_U - D_M)$. When using three geostationary satellites as described above, the additional measurement required is the altitude of user **10** measured from a reference datum. This altitude is accurately predictable for most users on the Earth's surface. However, knowing the user's altitude is not a critical requirement of this invention since additional satellite measurements are used as is described elsewhere.

Finally, in order to provide user **10** with the precise locations of geostationary satellites **20***a–c* as required for Eq. (3), pseudorange measurements of geostationary satellites **20***a–c* are made with reference to at least four remote tracking stations such as remote tracking stations **16***a–b* of FIG. **1**. The measurements are made by receivers located at these fixed known sites and are transmitted to master control facility **12**. Master control facility **12** then computes from pseudorange measurements made at tracking stations **16***a–b* and those at master control facility **12** to accurately determine the position of each of satellites **20***a–c*. The positions of satellites **20***a–c* once calculated are then transmitted via communication link **18***c* to uplink facility **14** for modulation onto a carrier signal and transmission to remote user **10**. Pseudorange data is calculated from signals received from the navigation satellites which take the form of Equations 1–2 above and common pseudoranges errors likewise be eliminated by differentially correcting.

Remote user **10** receives pseudoranges measured at master control facility **12** with respect to geostationary satellites **20***a–c*, at tracking stations **16***a–b* with respect to geostationary satellites **20***a–c*, and at master control facility **12** with respect to navigational satellites **30***a–d*. User **10** collects these measurements along with the pseudorange measurements made at remote user **10** with respect to geostationary satellites **20***a–c* and with regard to navigational satellites **30***a–d* to create a single user data set. This user data set is then separated into subsets.

The first subset contains unknown errors which must be determined from the data and can be considered a trial group. The second subset contains data with much smaller errors relative to the trial group such that it can be considered a control group. The data of both groups is applied to conditional error processing module wherein very accurate estimates of the error in the trial group are determined.

The conditional error process can be explained from a mathematical perspective. Assuming the vector Z to be defined as:

$$Z=HX+V \quad [5]$$

where

X≡an unknown vector representing the user's location

H≡the linear relationship between X and Z; and

V≡as vector comprised of random errors, the least squares solution for X is:

$$X^*=(H^TH)^{-1}H^TZ, \quad [6]$$

where H^T is the transposition of H. The residual after the least squares fit is:

$$R=Z-HX^*=(I-H(H^T)^{-1}H^T)Z=MZ \quad [7]$$

where I is the identity matrix and M is an idempotent transformation.

The residual vector R is defined by the single user data set comprised of differentially corrected GPS measurements and geostationary satellite measurements. Thus, when the user data set is partitioned into control and trial subsets, this is a partitioning of the vector components of the residual vector R. The differentially corrected GPS measurements are almost always the most accurate because the reference signal is visible both the user's location and at the known reference site. Longitudinal measurements to geostationary satellite such as satellites **20***a–c* could, however, be substituted as a control group in an alternative, lesser preferred embodiment. The differentially corrected GPS measurement are consequently used as the control group.

The residuals for the control group are assumed to be zero and are used to minimize the residuals for the entire data set based on that assumption. Z* is obtained by accumulating the elements of M in Eq. (7) over a prescribed period of time and then partitioning the accumulated M and culling the submatrices resulting from the control group residuals. Z* then is comprised of "conditional errors" in the trial group measurements and can be applied to the trial group subset (i.e., geostationary satellite measurements) to obtain more accurate measurements and, hence a "fix".

The conditional error processing module is illustrated in FIG. **7** and the processing algorithm in flow chart form in FIG. **8**. Conditional error processor **76** in FIG. **7** receives its input data from both groups, the trial group at input **72** and the control group at input **74**. The control group at input **74** in the preferred embodiment is the subset comprised of differentially corrected GPS measurements and the trial group at input **72** is the geostationary satellite measurements. Conditional error processor **76** then zeros out a set of accumulators and begins the iterative process for a predetermined period of time.

The iterative process begins by performing a least squares solution for all measurements including those in both the trial group and the control group. The differences (residuals) between the data in the trial group and the solution is determined from a linear mapping of all data, and the differences are stored and accumulated as a linear mapping of the raw data. The differences between the data in the control group and the solution are assumed to be zero and are also accumulated as a linear mapping. This iterative process in the preferred embodiment is performed for a period of approximately one to two minutes.

At the end of the iterative process, the conditional errors are computed by appropriately partitioning the accumulated linear mappings of raw data so that the differences of the control data are culled, inverting the resulting matrix, and then processing the accumulated residuals to determine the errors in the data of the trial group. The result is a new data set containing "conditional errors" that are applied to the original trial group subject (i.e., geostationary satellite measurements) to minimize the overall residuals. Processing then returns to the next accumulation cycle.

The output of conditional error processor **76** then consists of corrections **78** for the trial data **72**. The corrected trial data is then grouped again with the control group data and processed using a conventional standard processor **75**. Statistical processor **75** in the preferred embodiment implements a Kalman filter as is well known to those of ordinary skill in the art. Output **79** of statistical processor **75** then consists of accurate positional coordinates as a function of time.

It is an essential characteristic of the conditional error processing that the accuracies of the error estimates must be the highest possible given the total amount of data available to remote user **10**. They must be higher, for example, than if a simple comparison was made between the trial and control group of measurements. This is accomplished in conditional error processing by comparing the errors of all data that has been optimally combined via least square fitting procedure thus insuring the results will have to smallest possible statistical uncertainty.

By using the pseudoranges measured at remote control facility **12** with respect to navigational satellites **30***a–c* as the control group, the uncertainties in the error estimates will be several times less than the readout associated with the measurements in the control group, i.e., the differentially corrected GPS pseudo-ranges alone. Thus, the effects of residual unknown errors in the GPS data will have minimum effect on the accuracy of the error estimate corrections.

Geostationary satellites **20***a–c* function as fixed relays and can be replaced by radio navigation towers **36***a–b* shown in FIG. **1** in an alternative preferred embodiment. As shown in FIG. **6**, radio navigation towers **36***a–b* transmit signals via signal paths **38***a–b* to remote user **10** whereupon remote user **10** extracts measurements from the system that are proportional to the range of each shore station. Measurements extracted from signals **38***a–b* can be represented by Equation 4 below:

$$Z_S=R_S+N_S+B_S \quad [4]$$

where

Z_S=vector of the measured ranges;

R_S=vector of the true ranges to shore stations **36***a–b*;

N_S=measurement noise; and

B_S=instrumental biases.

Since the exact locations of radio navigation towers **36***a–b* are known, there are three unknowns and the users coordinate position can be determined therefrom without the need for tracking stations **16***a–b* or associated measurements. This information is then used along with GPS measurements taken as previously described to establish the single user data set for the conditional error processor.

It is therefore evident that the invention claimed herein may be embodied in alternative and equally satisfactory embodiments without departing from the spirit or essential characteristics thereof. The preferred embodiments disclosed above must consequently be considered illustrative and not limiting of the scope of the invention.

What is claimed is:

1. A method for determining positional coordinates, comprising the steps of:

transmitting an unmodulated first plurality of signals to a plurality of fixed relays from a control facility;

receiving the unmodulated first plurality of signals from the fixed relays and an unmodulated second plurality of signals from a plurality of navigational satellites at the control facility and at a remote location;

modulating the unmodulated first plurality of signals and the unmodulated second plurality of signals received at the control facility and retransmitting the modulated first plurality of signals and the modulated second plurality of signals to the remote location;

receiving the modulated first plurality of signals and the modulated second plurality of signals from the control facility at the remote location; and

processing the unmodulated first plurality of signals, the modulated first plurality of signals, the unmodulated second plurality of signals, and the modulated second plurality of signals received at the remote location to minimize errors in the data in the unmodulated first plurality of signals and in the modulated first plurality of signals with the data in the unmodulated second plurality of signals and in the modulated second plurality of signals to obtain accurate positional coordinates.

2. The method of claim **1**, wherein the step of processing to obtain positional coordinates further comprises the steps of:

performing a least-squares fit with the ranging data from said modulated second plurality of signals and from said unmodulated second plurality of signals and the positioning data from said unmodulated first plurality of signals and said modulated first plurality of signals;

accumulating the differences between the ranging data and the positioning data and the data obtained for the least-squares fit;

storing the differences between the ranging data and the positioning data and the data obtained from the least-squares fit;

accumulating the data obtained for the least-squares fit;

storing the data obtained for the least-squares fit;

partitioning the accumulated least-squares fit data to segregate the ranging data;

inverting and operating on the accumulated differences to determine the errors in the segregated data;

correcting the errors in the segregated data to obtain accurate positional coordinates.

3. The method of claim **1**, wherein the plurality of fixed relays are further comprised of at least one of a geostationary satellite or a shore-based radio navigation station.

4. The method of claim **1**, wherein the step of modulating relayed ranging data comprises modulating the relayed ranging data using spread-spectrum techniques to include pseudorandom code modulation at preselected chipping and code repetition rates.

5. The method of claim **1**, wherein the unmodulated first plurality of signals, the modulated first plurality of signals, the unmodulated second plurality of signals, and the modulated second plurality of signals are transmitted as spread-spectrum signals.

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